Analysis of Infrared Measurements of Microbreaking and Whitecaps

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LONG-TERM GOALS

The long-term goals are to develop passive and active infrared techniques to study air-sea interaction.

OBJECTIVES

The objectives are to use passive infrared techniques to determine the influence of wave breaking on surface roughness modulation relevant to radar backscatter and to develop active IR techniques relevant to turbulent fluxes of momentum and heat.

APPROACH

Our efforts have focused on analysis of data taken during the FAIRS (Fluxes Air-sea Interaction and Remote Sensing) Experiment, which took place on the *R/P FLIP* off Monterey, CA in fall 2000. Two main topics of investigation have been pursued. The first topic is to investigate the modulation of ocean skin temperature by swell waves and determine how microscale breaking waves detected using passive infrared techniques [*Jessup et al.*, 1997] are related to bound, tilted waves that affect microwave backscatter [*Plant*, 1997]. The skin temperature modulation has been investigated using data from the calibrated narrow field-of-view radiometer and an infrared imager that was co-located with the illuminated area of a scatterometer deployed by Bill Plant of APL-UW (see his annual report in this volume). The second topic is to investigate the relationship of the heat transfer velocity measured using active infrared techniques to momentum and heat fluxes. This technique uses infrared imagery to measure the decay of a small spot on the surface heated using a CO_2 laser. We use results of our laboratory experiments to guide the field work [*Siddiqui* et al., 2002].

RESULTS

During a previous experiment on *FLIP*, *Jessup and Hesany* [1996] observed modulation of skin temperature, T_s, by swell. They showed coincident time series of T_s and surface displacement, η, and analyzed the modulation in terms of a transfer function with magnitude T_0 and squared coherence γ^2. They found that T_0 depended on the bulk-skin temperature difference ΔT. The 24-hours time series of T_0, γ^2, and ΔT from FAIRS in Figure 1 show similar modulation characteristics. During this same time period, the radar cross-section measured by the scatterometer was also modulated, as shown in the time series of σ^o, T_o, and η in Figure 2.

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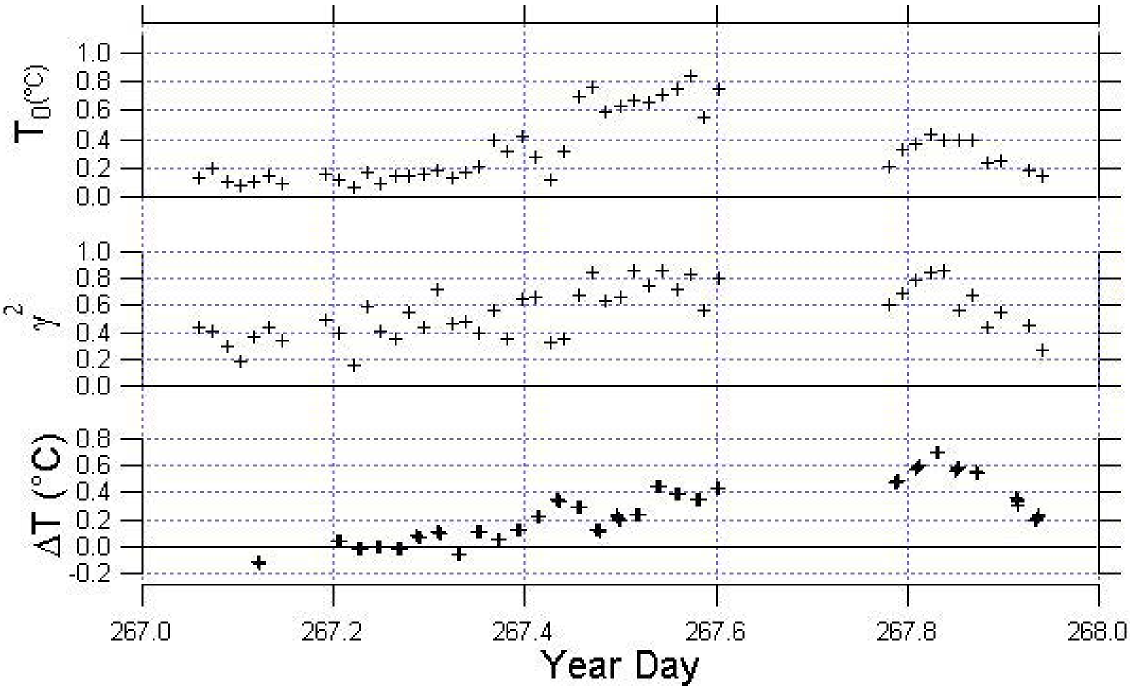

Figure 1. Time series of the magnitude of the modulation transfer function, T_0, squared coherence, γ^2, and bulk-skin temperature difference, ΔT, for a 24-hour time period. During the time when ΔT increased from zero to 0.4 °C, T_0, increased from less than 0.2 to about 0.8 and γ^2 increased from 0.4 to greater than 0.8.

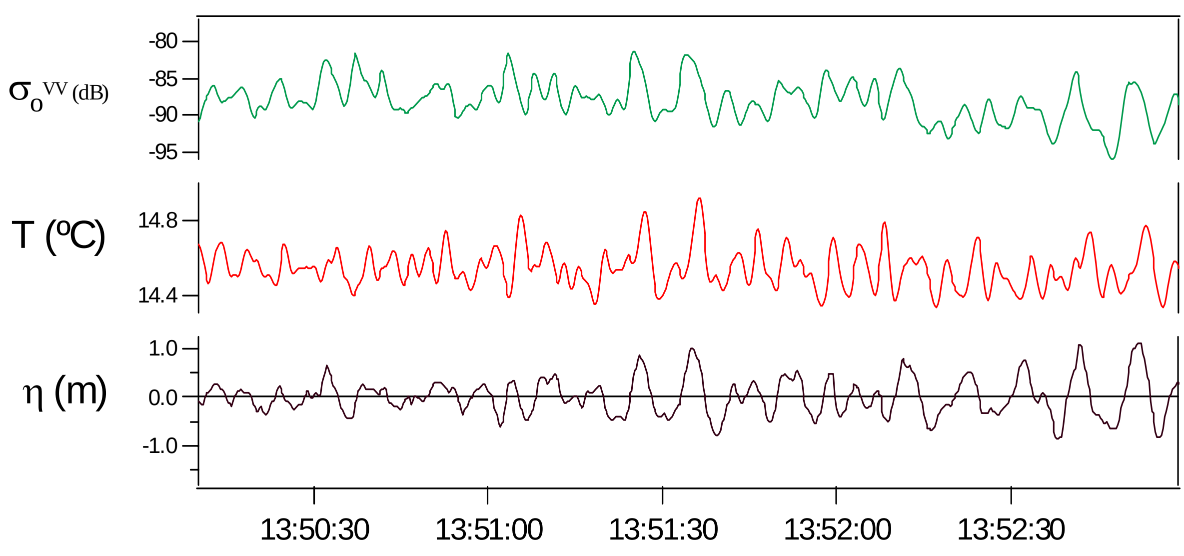

Figure 2. Time series of VV-polarized radar cross section, σ^o, skin temperature T_s, and surface displacement η during the period shown in Figure 1. Comparison of the time series show that σ^o and T_s are both modulated by η.

During FAIRS, we compared infrared imagery with VV and HH Doppler spectra from the coincident Ku-band scatterometer to determine the extent to which microbreaking may influence this modulation.

Earlier investigations of microwave backscatter [*Jessup et al.*, 1992] showed that whitecaps can produce large transient increases in σ^o, known as sea spikes, with a polarization ratio, VV/HH, of unity. In the absence of whitecaps, the Doppler spectra are characterized by a single peak and VV/HH < 1. When a whitecap occupies a significant portion of the illuminated area, the Doppler spectra can exhibit two peaks. The first peak at low frequency tends to have VV/HH < 1 while the higher frequency peak tends to have VV/HH≈1. These characteristics are illustrated in Figure 3, which show simultaneous infrared images and Doppler spectra.

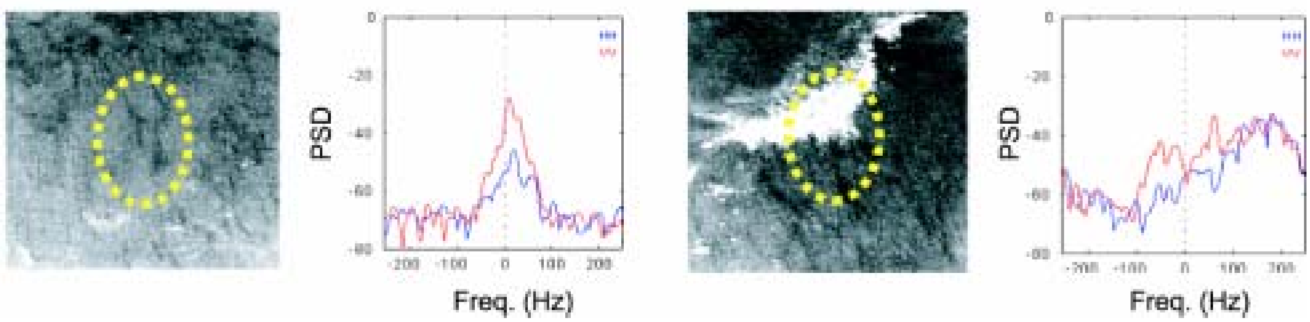

Figure 3. Infrared image of sea surface and corresponding Doppler spectra for the case of no whitecap (left) and a large whitecap entering the 3-dB illuminated area, shown as a dotted ellipse. For the case of no whitecap, the spectra have a single peak with VV/HH<1. For the case of the whitecap, the spectra show a peak near zero frequency with VV/HH<1 and a second higher frequency peak with VV/HH≈1. The image size is approximately 4.8 m on a side and the elliptical illuminated area has major axis length of 2 m and a minor axis length of 1 m (with the major axis oriented along the vertical axis of the image).

We have found that these characteristics of the Doppler spectra heretofore associated with large whitecaps can also be found for small whitecaps and even microbreaking waves, for which no foam generated by bubbles is observed. An example of the effect of a small whitecap on the Doppler spectra is given in Figure 4. The thermal disruption of the skin layer due to the breaking wave is apparent in the sequence of infrared imagery shown in the top row of Figure 4. The video image in the bottom left shows a small whitecap. The Doppler spectra exhibit two peaks with characteristics similar to that due to the whitecap shown in Figure 3. The effect of a microbreaking wave on the Doppler spectra is illustrated in Figure 5. The area of temperature change due to the disruption of the cool skin layer by the microbreaking wave is outlined by a red dashed area that propagates down the image, while the video image shows no sign on a whitecap. While the peak Doppler shift is not as large as in Figure 4, the polarization ratio is near unity.

These examples demonstrate the potential for using simultaneous infrared, video, and microwave measurements to examine the specific wave-related mechanisms affecting Doppler spectra. In surveying the available data, we have found that the ability to detect microbreaking waves is dependent on the magnitude of ΔT. Because ΔT decreases rapidly with increasing wind speed, we investigated the use of an active infrared technique that is not dependent on a cool skin layer being present. A CO_2 laser is used to heat a small spot on the surface and the decay rate of the heated spot is measured from sequences of the infrared imagery. We are currently investigating the modulation of the decay rate by swell wave as a more robust method.

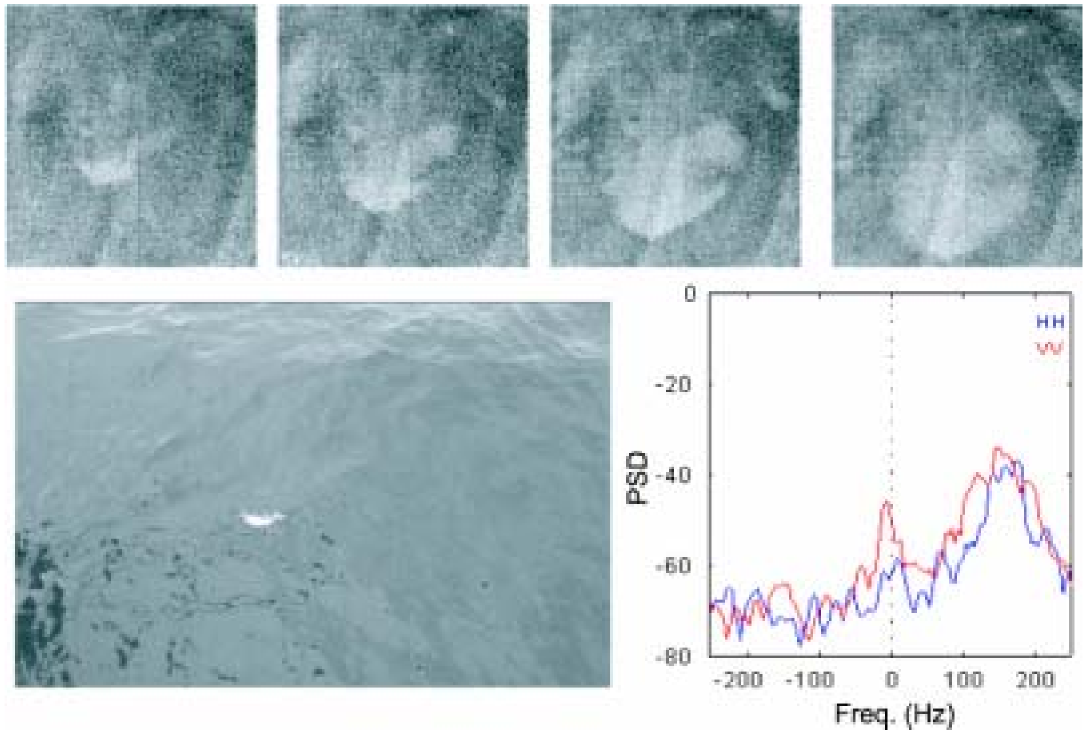

Figure 4. Example of the effect of a small whitecap (crest length ≈ 1 m) on the Doppler spectra by comparison of IR image sequence (top row), video image (bottom left), and Doppler spectra (bottom right). IR image size same as in Figure 3, video image size 9 m (V) by 15 m (H). Spectra show high frequency peak with VV/HH≈1.

By computing the average decay rate over several minutes, the active infrared technique can be used to measure the average heat transfer velocity, k_{heat} [*Jähne and Haußecker*, 1998; *Zappa*, 1999]. Subsequent to the FAIRS experiment, we also employed the active IR technique during the GasEx 2001 cruise on the NOAA R/V *Ronald H. Brown*. The wind speed dependence of k_{heat} for the combined FAIRS and GasEx 2001 data set is shown in Figure 6 and covers a range of wind speed from 1 m s^{-1} to nearly 15 m s^{-1}. To the best our knowledge, these experiments are the first time the active infrared technique has been successfully employed in the field under such a wide range of wind conditions. The agreement between two data sets is excellent and the dependence on wind speed suggests that further investigation of mechanisms controlling k_{heat} is warranted. We are in the process of incorporating the friction velocity and heat flux measurements from the two data sets into our analysis.

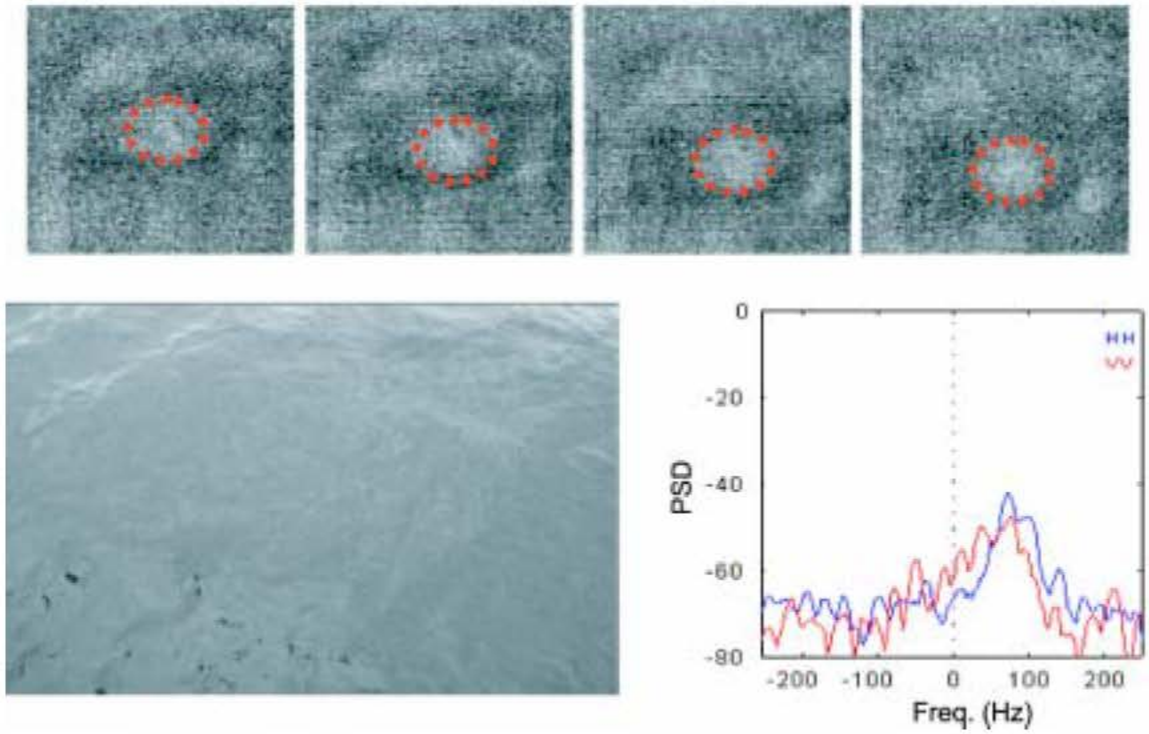

Figure 5. Example of effect of microbreaking wave (crest length<1 m) on Doppler spectra IR sequence, video image, and spectra as in Figure 4 except IR image 2.4 m on a side. Spectra show high frequency peak with VV/HH≈1.

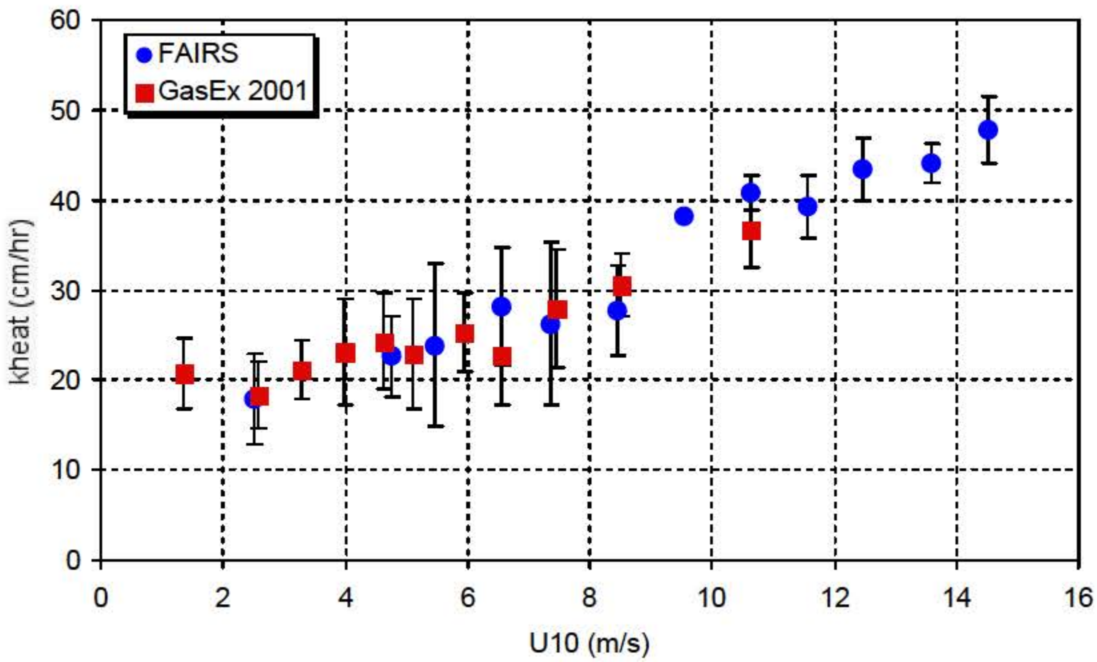

Figure 6. Wind speed dependence of heat transfer velocity, k_{heat} derived from the active infrared technique for the FAIRS and GasEx 2001 experiments. [The k_{heat} values increase linearly from 20 cm hr^{-1} to nearly 50 cm hr^{-1} over a wind speed range of 1 m s^{-1} to 15 m s^{-1}. The FAIRS wind speed ranges from roughly 2 m s^{-1} to 15 m s^{-1} while the GasEx 2001 data range from about 1 m s-1 to 11 m s^{-1}.]

IMPACT/APPLICATIONS

The research demonstrates the value of combined infrared and microwave measurements for understanding scattering mechanisms. Continued development of the active infrared technique will determine its utility for remote measurements of turbulent mixing due to wave breaking.

RELATIONSHIP TO OTHER PROGRAMS OR PROJECTS

We are working closely with Bill Plant on correlation of the infrared and microwave data. This work also related to a collaborative effort with W. E. Asher (APL-UW) to investigate the role of microbreaking in gas transfer funded by NSF.

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